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Environmental and economic assessment of durability of energy-using products: Method and application to a case-study vacuum cleaner

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A B S T R A C T

The article focuses on the quantitative assessment of the benefits and/or burdens of extending the lifetime of products. Longer lasting products can be less efficient than newer one, implying higher energy consumption, environmental impacts and costs. The article illustrates a set of indicators, named “Pro-EnDurAncE” (Environmental and Economic Assessment of Durability of Products), developed for the assessment of products durability from both environmental and economic perspectives. Pro-EnDurAncE indicators have been structured to capture various relevant aspects, as the impacts and costs of the studied product and of potentially replacing products, the maintenance and repair, the lifetime extension and the use of energy and auxiliary materials during the operation. The proposed indicators were illustrated upon a case-study vacuum cleaner. It resulted that extending the lifetime of this product produce environmental and economic benefits in the large majority of scenarios considered. For example, when the impacts of repair are negligible, the extension of the lifetime by 250 h (i.e. 5 years) avoids around 4.2% of Global Warming Potential impact compared to the replacement of the vacuum cleaner with a new one 15% more energy efficient. Analogously, despite the occurring repair costs, the economic benefits for extending the lifetime by 250 h are equal to 40€ (i.e. about 8.6% of the life cycle costs) compared to the replacement with a new product 15% more energy efficient. The article concludes that the Pro- EnDurAncE indicators are applicable to investigate the durability of products in several different scenarios and they are robust and flexible since the assessment can based on a large number of parameters and different scenarios. These indicators can be used to assess product at the design stage or to support policy measures to promote more durable products.

1. Introduction

Based on several definitions available in the scientific literature, durability of products is intended as the ability of products or materials to maintain their properties, their functions and performances over the time (Kostecki, 1998; Rose, 2000; ISO/TR 14062, 2002; Mora, 2007). The relevance of this topic is proved by the wide discussion in the literature from different points of view (technical, environmental, economic and social) and by several national and international standards for durable products (BSI, 2011; CEN, 2002; ISO, 2007, 1998, 1989; ONR, 2014).

In the last decades the interest on the durability of products increased particularly in relation to the potential environmental, economic and social benefits which could derive from extending the lifetime of products (especially in terms of waste prevention and material savings during the life cycle). The relevance of durability for a cleaner production has been acknowledged in strategic policy documents as the European Integrated Product Policy (IPP) (EC, 2001). The ‘Circular Economy package’, published by the European Commission on December 2015, stressed the durability as one of the key aspects for the resource efficiency of products, particularly relevant for the sustainable production and the consumption pillars (EC, 2015a). For example it is stated that a “better design can make products more durable or easier to repair, upgrade or remanufacture” (EC, 2015a). The European Ecodesign Directive also suggests that the lifetime extension of products could be achieved via different strategies as “minimum guaranteed lifetime, minimum time for availability of spare parts, modularity, upgradeability, reparability”, but it also underlines the relevance of adopting cost-effective measures valued on a life cycle perspective (EU, 2009). One of the first follow-up action of the European Union

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(EU) Action plan for a Circular Economy was the mandate to European Standardization Organizations to develop standards for the assessment and measurement of the material efficiency of products (EC, 2015b). Among these, one of the planned standardisation deliverable concerns the "definition of parameters and methods relevant for assessing durability".

These policy principles can be implemented into operative requirements to promote more durable products within various mandatory and voluntary policies. These requirements should be applied to products, or some of their components, and they should relate to various stages of the product life cycle (i.e. manufacturing, maintenance and repair, reuse, remanufacturing and refurbishment) (Bundgaard et al., 2014; EC, 2015a, 2015c). Some examples of durability requirements have been enforced in the EU concerning electric lighting systems (EC, 2009a, 2009b) and vacuum cleaners (EU, 2013a). Moreover, also some national and international voluntary instruments promoted durable products, as for example the criteria for Green Public Procurement and eco-labelling schemes for various product groups (EC, 2013a, 2011, 2009c; Nordic Ecolabelling, 2015).

Also the scientific literature identified several features that can affect the durability of products as: the resistance and deterioration of the materials; the easiness of reparation and upgrade; the costs for repairs; the availability of information and warranties; the product appearance. Many authors highlighted the strict relationship between product's durability and user behaviours (e.g. improper use, attitude to maintain and repair the products versus their discard and replacement), which in turn are affected by a mix of technical, economic and social aspects (Barba-Gutiérrez et al., 2008; BIO by Deloitte, 2013a, 2013b; Boulos et al., 2014; Cooper, 2012, 2005; Kemna, 2011; Kemna et al., 2005; van Nes and Cramer, 2006).

The successful adoption of durable products by consumers is strongly related to the economic viability of the products, including: purchasing costs (generally higher for longer lasting products); energy costs; maintenance and repair costs. Several studies stressed the relevance of following the manufacturer's instructions for maintenance to avoid a reduction of the lifetime of the product and overall higher costs (Brook Lyndhurst Ltd, 2014; WRAP, 2011). Market and economic barriers for durable products (especially high costs for the repair, availability of spare parts and/or updated software) could be even more important than technical barriers (BIO by Deloitte, 2016). On such purpose, various initiatives supporting the repair of the appliances have been developed at European level as, for instance, the creation of independent repair organisations (e.g. "Repair Café") and the creation of web communities (e.g. 'IFIXIT') to instruct people on how to repair their products (BIO by Deloitte, 2016). Moreover, the certification and labelling of the repair services compliant with specific quality criteria could allow consumers to have access to high quality repair services (BIO by Deloitte, 2016). All these initiatives are relevant for the widE−spreading of a new culture for repair in Europe, in which repair is attractive for consumers (Maurer and Pachl, 2015).

However, a prolonged lifetime can produce adverse effects. For instance, Sneck (1981) evidenced more than 30 years ago that "negative aspects of excessive durability are caused by the use of unjustifiably durable and usually much more expensive materials, construction techniques or designs". The operation of not efficient household appliances for a longer time can cause higher impacts during the operation phase (especially in terms of energy consumption) (Bundgaard et al., 2014).

All the above mentioned considerations point out the relevance and the complexity of the assessment of durable products. In particular, it is underlined the necessity of a multi-disciplinary approach to account for potential pros and cons related to the use of longer lasting products.

1.1. Aims of the article

The article introduces a set of indicators, named "Pro-EnDurAncE" (Environmental and Economic Assessment of Durability of Products), for the assessment of products' durability from both environmental and economic perspectives. These indicators are part of the more comprehensive method "REAPro" (Resource Efficiency Assessment of PROducts) developed by the Joint Research Centre (Ardente and Mathieux, 2014a), and aiming at assessing the resource efficiency of energy-using products[1] (EuPs) and based on various different criteria, including durability. These Pro-EnDurAncE indicators assess, in a life cycle perspective, the potential benefits or burdens associated with the extension of the lifetime of products.

Compared to previously developed indicators for durability as described in Ardente and Mathieux (2014b), the Pro-EnDurAncE indicators have been elaborated to capture additional environmental aspects, and enlarged to comprise the economic dimension of durability. The co-presence of these two dimensions can permit a wider and more exhaustive analysis of longer lasting products. The article aims as well at illustrating how the design and use of more environmentally-friendly products could be promoted in an economically viable way. Despite their potential relevance, social aspects were considered out of scope since their analysis would involve quality aspects that cannot be easily modelled by quantitative parameters.

The next sections illustrate and discuss the proposed indicators. In particular, section 2 summarises the review of the scientific literature to identify key aspects for the durability of EuPs, whereas the proposed indicators are introduced in sections 3 and 4. The indicators were then applied to a case-study vacuum cleaner (VC) (section 5), and results were finally analysed and discussed in section 6.

2. Analysis of the durability of products in the scientific literature

The durability of products has been analysed by various authors with different methodological approaches. The complexity of this analysis is essentially related to the multiplicity of factors affecting durability and the intrinsic uncertainty of assessing future scenarios (Ardente and Mathieux, 2014b). Table 1 presents a summary of the key aspects on durability discussed in some relevant studies from the literature.

It was observed that the majority of the studies analysed the durability of products focusing on the extension of lifetime. These two concepts are so linked that they are often interchangeably used. However, extending the lifetime not necessarily implies a more durable product, since it is not granted that it will still maintain its performance and functions. Moreover, extending the lifetime does not necessarily represent the optimal strategy for the EuPs (Ardente and Mathieux, 2014b; Sneck, 1981). AEA (2009), Cooper (1996), Okumura et al. (2001) and Planet Ark (2007) highlighted that he manufacturing of more durable products could imply the use of higher amount of materials, materials with higher quality or more complex processes, implying higher impacts (environmental and economic) for the manufacturing. Other authors stressed the relevance of additional features that can imply

[1] Energy-using products have been defined as means products which, once placed on the market and/or put into service, are dependent on energy input to work as intended (EC, 2005).

Table 1
Literature review on studies dealing with relevant aspects of durability of products.

N°	Authors	Durability	Lifetime indications	Environmental aspects	Economic aspects	Consumer role
1	(Rose, 2000)	X	X	–	–	X
2	(Ernzer and Birkhofer, 2003)	–	X	X	–	X
3	(Horie, 2004);	X	X	–	X	X.
4	(Abele et al., 2005)	–	X	X	X	X
5	(Cooper, 2005)	X	X	X	X	X
6	(Kemna et al., 2005)	X	X	X	X	X
7	(Kobayashi et al., 2005)	–	X	X	–	X
8	(Allenby, 2006)	X	X	–	X	X
9	(Barba-Gutiérrez et al., 2008)	–	–	X	X	X
10	(AEA, 2009)	X	X	X	X	X
11	(Wong, 2009)	X	X	X	X	–
12	(Boustani et al., 2010)	–	X	X	X	–
13	(Cooper, 2010)	X	X	–	X	X
14	(Murakami et al., 2010)	X	X	–	–	X
15	(Maurer, 2010)	X	X	–	–	X
16	(WRAP, 2010)	–	X	–	–	X
17	(Brook Lyndhurst, 2014)	X	X	–	–	X
18	(WRAP, 2011)	X	X	–	X	X
19	(Huisman et al., 2012)	X	X	–	–	–
20	(BIO by Deloitte, 2013c)	X	X	–	X	X
21	(Monier et al., 2013)	–	X	–	–	–
22	(Tasaki et al., 2013)	X	X	–	–	X
23	(Boulos et al., 2014)	X	X	–	X	X
24	(Debaveye et al., 2014)	X	–	–	–	–
25	(TNS, 2014)	X	–	–	X	X

the product's replacement, as the wear-out of products and the technological evolution of products in the market (Dewulf and Duflou, 2004; Kostecki, 1998; Rose and Stevels, 1999).

The majority of the investigated studies also referred to economic aspects belonging to different life cycle phases. This confirms that the assessment of the benefits of longer lasting products should take into account, as far as possible, also economic variables (BIO by Deloitte, 2016; Murakami et al., 2010; Prakash et al., 2015).

The lifetime of products is strictly related to their preventive maintenance (e.g. substitution of components, cleaning of the products, etc.) and repair operations (Cooper, 2010; Kobayashi, 2005). Manufacturers should promobib_AEA_2009te durable products through the ease of disassembly of key components, the availability of spare parts and the provision of information and tools for the repair (Cooper, 2005; Kostecki, 1998; WRAP, 2011).

According to a recent Eurobarometer survey (TNS, 2014), about 77% of European citizens claim to prefer repairing their products instead of purchasing new ones, however 39% of the interviewed people think that repairing a broken product is often difficult or economically disadvantageous. Despite the apparent preference for repair and the expected economic savings, the buying habits and other consumer behavioural aspects seem to hinder the uptake of repair activities (BIO by Deloitte, 2016). Already the SCOPE project on durability of household appliances, based on interviews undertaken in the United Kingdom a decade ago, observed that over two-thirds of the users considered discouraging the cost for repairing Electric and Electronic Equipment (EEE) (Cooper, 2005). The cost of maintenance and repair operations (often related to the time spent for the labour) is therefore a key factor for the consumer when deciding about discarding an old or broken product. In fact, the substitution of a product may be more convenient than its repair from an economical point of view (Kostecki, 1998; Prakash et al., 2015).

Notably, durable products needs to overtake fashion trends (Cooper, 2005; Stahel, 2013). The needs of consumers (i.e. in terms of functionality, size, appearance, etc.) might change in due course, thus making the extended lifetime and the associated investments obsolete (Ardente and Mathieux, 2014b). According to the Eurobarometer survey (Stahel, 2013; TNS, 2014), more than 37% are willing to buy second-hand household appliances (TNS, 2014). However, this seems not to be confirmed by the market of reused EEE, which is still marginal in the EU. In order to increase acceptability and penetration in the market of more durable products, highly credible and unambiguous information to consumers are essential, including information about the quality of repair and refurbishing services (BIO by Deloitte, 2013a, 2013b, 2013c; Cooper, 2005; van Nes and Cramer, 2006; WRAP, 2011).

This literature review pointed out the relevance of considering multiple life cycle aspects related to the durability of products. Both environmental and economic features should be simultaneously assessed in order to identify pros and cons of durability improvement of products and to support consumer choices.

3. Environmental assessment of durability: updates

An initial approach for the environmental assessment of the durability of EuPs were developed by Ardente and Mathieux (2014b). This assessment was based on the comparison of two scenarios in a life cycle perspective: Base-case scenario (1) and Durability scenario (2). Scenario (1) assumed the substitution of the product (A) with a more energy-efficient one (product B) after its average lifetime (T); Scenario (2) assumed the substitution of the product (A) after a longer time frame (i.e. T + X) than in Scenario (1). All the symbols used in the present section are illustrated in Table 2. Successively, a durability index was defined by Ardente and Mathieux (2014b) as the difference between the environmental impacts in those two scenarios, divided by the impacts of the life cycle of the product:

$$D'_n = \frac{\frac{P_n}{T}\cdot X + \frac{E_n}{T}\cdot X - (1-\delta)\cdot U_n\cdot X - R_n}{P_n + U_n\cdot T + E_n}\cdot 100 \qquad (1)$$

This index can be referred to different impact categories "n", as those applied in the Life Cycle Assessment (LCA) methodology (ISO, 2006). According to Ardente and Mathieux (2014b), items of formula (1) are calculated based on life cycle inventory data of materials, energy sources and process, as provided in commercial databases and software for LCA. Since different values of the index

Table 2
Symbols and abbreviations in the environmental formulas (section 3).

Parameter	Description	Unit of measure
$AU_{A,n}$	Environmental impact for category “n” for the auxiliaries' materials consumption for product (A)	[unit/time]
$AU_{B,n}$	Environmental impact for category “n” for the auxiliaries' materials consumption for product (B)	[unit/time]
AU_n	Environmental impact for category “n” for the auxiliaries' materials consumption	[unit/time]
D'_n	Durability index for the impact category “n”	[%]
E_A	Environmental impact for category “n” for the EoL treatments of product (A)	[unit]
$E_{A'}$	Environmental impact for category “n” for the EoL treatments of product (A′)	[unit]
E_B	Environmental impact for category “n” for the EoL treatments of product (B)	[unit]
$E_{B,n}$	Environmental impact for category “n” for the EoL treatments of product (B)	[unit]
E_n	Environmental impact for category “n” for the EoL treatments of product	[unit]
$M_{A,n}$	Environmental impact for category “n” for the maintenance's materials consumption for product (A)	[unit/time]
$M_{B,n}$	Environmental impact for category “n” for the maintenance's materials consumption for product (B)	[unit/time]
$P_{A,n}$	Environmental impact for category “n” for the production of product “A” (including the production of raw materials and manufacturing)	[unit]
$P_{A',n}$	Environmental impact for category “n” to produce a more durable product (including all the impact for the production of raw materials and manufacturing)	[unit]
$P_{B,n}$	Environmental impact for category “n” for the production of product “B” (including the production of raw materials and manufacturing)	[unit]
P_n	Environmental impact for category “n” for the production of the product (including raw materials and manufacturing)	[unit]
$R_{A,n}$	Environmental impact per unit of time for category “n” for additional treatments (e.g. repairing, refurbishment) necessary for the extension of operating time T_A	[unit]
R_n	Environmental impact per unit of time for category “n” for additional treatments (e.g. repairing, refurbishment) necessary for the extension of operating time T	[unit]
T	Average operating time of product	[time]
T_B	Average operating time of product (B)	[time]
$u_{A,n}$	Environmental impact for category “n” for the energy consumption during the use phase of product (A)	[unit/time]
U_n	Environmental impact per unit of time for category “n” for the use of product	[unit/time]
U_n	Environmental impact per unit of time for category “n” for the use of product	[unit/time]
u_n	Environmental impact for category “n” for the energy consumption during the use phase	[unit/time]
X	Extension of operating time of the product	[time]
α	Percentage representing the higher impact to produce a more durable product	[%]
δ	Variation of the energy consumption impact of product (B) compared to (A)	[%]
γ	Percentage representing the variation of the impacts due to the production of the new product “B” substituting the product “A”;	[%]

are usually obtained for different impact categories, aggregation and weighting of different values could be possible. However, weighting of the impact has been considered as out-of-scope for this analysis, since largely uncertain and highly disputed in the scientific community.

The durability index is here revised to include some additional parameters relevant for the durability assessment, as identified in the previous literature review. In particular, formula (1) was revised to take into account: impacts due to the use of auxiliary materials during the operation; impacts due to maintenance; and impacts due to potential changes in the manufacturing of the replacing product (B). The two revised scenarios used for the calculation of the new durability index are illustrated in Fig. 1.

Moreover, Ardente and Mathieux (2014b) assumed that the manufacturing of the replacing products (B) had the same impacts as those of the base-case product (A). However, it is recognised that

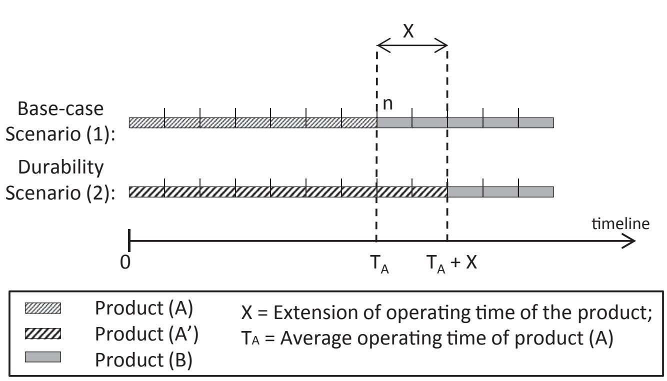

Fig. 1. Scenarios used for the environmental assessment of the durability of products.

after several years of using the product (A), the manufacturing of the new products can differ due, for instance, to the use of different materials or new technologies during the production process. This aspect can be appraised through an additional parameter “γ” representing the variation of the impacts ($P_{A,n}$) due to the production of the product (A) compared to the production of the replacing product ($P_{B,n}$).

$$\gamma = \frac{P_{B,n}}{P_{A,n}}\cdot, \quad \gamma > 0 \tag{2}$$

The impacts to produce (B) are not necessarily higher than the impacts to produce the base-case product (A). For example, values of “γ” higher than 1 imply that the production of the product (B) has lower impacts due, for example, to an increased environmental efficiency of the manufacturing.

In Ardente and Mathieux (2014b) it was assumed for simplicity that, in both the scenarios, the production of the base-case product and of the durable product had the same impacts. However, it is recognised that the production of a more durable products (A′) could imply additional burdens compared to the base-case product (A), for instance due to the use of higher amount of materials, materials with higher quality or different materials. Although less relevant, some additional impacts for durable products could be related to other aspects as: longer design processes, development of innovative machineries, more tight testing, etc. (Kostecki, 1998; Mora, 2007; AEA, 2009). This difference among products (A) and (A′) is also visible in the two scenarios as described in Fig. 1. The durability index was revised to account for the impacts due to the production of the more durable product ($P_{A',n}$). These impacts can be estimated as a function of the impacts for the manufacturing of the base-case product (A), as:

$$P_{A',n} = (1+\alpha)\cdot P_{A,n}; \quad \alpha = \frac{(P_{A',n} - P_{A,n})}{P_{A,n}} \quad \alpha \geq 0 \tag{3}$$

The impacts of the EuPs during the use phase are largely related to the energy consumption, as observed by various authors (Abele et al., 2005; AEA, 2009; Cellura et al., 2014; Gandy et al., 2012; Hur et al., 2005; Kenma et al., 2005; Kobayashi et al., 2005; Kota and Chakrabarti, 2007; van Nes and Cramer, 2006). For this reason, Ardente and Mathieux (2014b) referred solely to the impacts of energy consumption during the operation. However, some products need auxiliary materials for accomplishing their duties (e.g. filters and dust-bags for vacuum cleaners). The accounting of the additional impacts due to auxiliary materials can be relevant for the assessment of durable products. Therefore the durability index was revised to account in general for all the environmental impacts during the use phase, as:

$$U_n = AU_n + u_n \tag{4}$$

It is also assumed that the product (A′) was designed to be more durable while not changing its functional characteristics. Therefore, the maintenance, the use of auxiliary materials and the energy consumption of products (A) and (A′) are assumed the same in the two scenarios (1) and (2) (i.e. $AU_A = AU_{A'}$; $M_A = M_B$; and $u_{A,n} = u_{A',n}$).

Based on the previous assumptions. The revised Durability index (D_n) is calculated as:

$$D_n = \frac{\frac{(\gamma-\alpha)\cdot P_{A,n}}{T_B}\cdot X + \left[\frac{E_{B,n}}{T_B}\cdot X + (E_A - E_{A'})\right] + (AU_{B,n} + M_{B,n} - AU_{A,n} - M_{A,n})\cdot X - (1-\delta)\cdot u_{A,n}\cdot X - R_{A,n}}{P_{A,n} + U_{A,n}\cdot T_A + E_{A,n}}\cdot 100 \tag{5}$$

It is observed that the impacts for repair (R_A) negatively affect the D_n, meaning that if repair operations occur to prolong the lifetime (for instance repairs or replacement of some components), then the more durable product can be less convenient from an environmental point of view. This confirms that reparability is a key aspect for the assessment of the durability of products, in line with the analysis of the relevant literature (section 2).

4. Economic assessment of durability

This section illustrates the development of a new index for the economic assessment of the durability of products, based on a similar approach to that applied for the environmental assessment. Two different scenarios are considered in order to assess the potential economic benefits/costs for consumer related to more durable product (Fig. 2). The Base-case scenario assumes the substitution of the base-case product (A) with a more energy-efficient one (B) after its average lifetime (T_A); the Durability scenario assumes the substitution of the product after a longer time frame. In particular, the time frame for the assessment is set from the time "zero" (corresponding of the purchase of base-case product) up the time (T_A + X). Thus, the expenditure occurring every year by the consumers for the operation, as well as the purchase price of product (B), the maintenance of both products (M_{At} and M_{Bt}), and the repair cost (R_A) are discounted in order to evaluate their present value through a Present Value Factor (PVF). End-

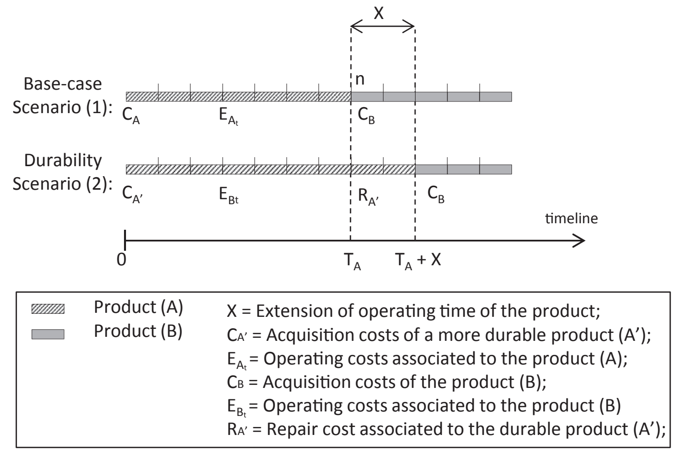

Fig. 2. Scenarios used for the economic assessment of the durability of products.

of-Life costs for consumers are assumed to be negligible. All the symbols used in all the present section are detailed in Table 3. The capital costs related to the product (B) (i.e. acquisition, operation and maintenance) up to the time (T_A + X) were proportionally divided over its lifetime (T_B). The total costs of the Base-case scenario can be expressed as:

$$C_{TOT,base\ \ case} = C_A + \sum\nolimits_{t=1}^{T_A}\left[\mathrm{PVF}_{t_B,i}(E_{A_t} + M_{A_t} + AU_{A_t})\right] + (\mathrm{PVF}_{t,i}C_B)\cdot\frac{X}{T_B} + \sum\nolimits_{t=1}^{X}\left[\mathrm{PVF}_{t_B,i}(E_{B_t} + M_{B_t} + AU_{B_t})\right] \tag{6}$$

Similarly, the total costs of the Durability scenario are calculated as:

$$C_{TOT,\mathrm{durable}} = C_{A'} + \sum\nolimits_{t=1}^{T_A+X}\left[\mathrm{PVF}_{t_A,i}(E_{A_t} + M_{A_t} + AU_{A_t})\right] + \mathrm{PVF}_{t,i}(R_{A'}) \tag{7}$$

The difference between the life cycle costs of the two scenarios is calculated as: $\Delta_{C_{TOT}} = C_{TOT,base\ \ case} - C_{TOT,\mathrm{durable}}$.

$$\Delta C_{TOT} = (\mathrm{PVF}_{t,i}C_A) + (\mathrm{PVF}_{t,i}C_B)\cdot\frac{X}{T_B} - (\mathrm{PVF}_{t,i}C_{A'}) + \sum_{t_B=1}^{X}\left[\mathrm{PVF}_{t_B,i}(E_{t_B} + M_{t_B} + AU_{t_B})\right] - \sum_{t_1=T_A+1}^{T_A+X}\left[\mathrm{PVF}_{t_A,i}(E_{t_A} + M_{t_A} + AU_{t_A})\right] - \mathrm{PVF}_{t,i}(R_{A'}) \tag{8}$$

Based on formula (8), it could be noticed that the difference between the total costs of scenarios (1) and (2) (i.e. ΔC_{TOT}) is dependent on: the difference between the price of the product (A) and the more durable product (A'), the price of the new product, the energy price, the costs due to maintenance and the auxiliary

Table 3
Symbols and abbreviations in the economic formulas (Section 4).

Parameter	Description	Unit of measure
AU_{At}	Auxiliaries components costs associated to the product (A)	[cost/time]
AU_{Bt}	Auxiliaries components costs associated to the product (B)	[cost/time]
$C_{A't}$	Acquisition costs of a more durable product (A′)	[cost]
C_{At}	Acquisition costs of the product (A)	[cost]
C_{Bt}	Acquisition costs of the product (B)	[cost]
$C_{TOT,base\ case}$	Total costs of the Base-case scenario	[cost]
$C_{TOT,durable}$	Total costs of the Base-case scenario	[cost]
e_A	Energy consumption during the use phase of product (A)	[unit]
E_{At}	Operating costs associated to the product (A)	[cost/time]
e_B	Energy consumption during the use phase of product (B)	[unit]
E_{Bt}	Operating costs associated to the product (B)	[cost]
E_T	Energy costs	[cost/unit]
i	Discount rate	[%]
M_{At}	Maintenance costs associated to the product (A)	[cost/time]
M_{Bt}	Maintenance costs associated to the product (B)	[cost/time]
PVF	Present Value Factor of the cash flow stream considered	[-]
R_A	Repair cost associated to the durable product (A)	[cost]
t	Generic period of time for which the cost is calculated	[time]
T_A	Operating lifetime of product (A)	[time]
$T_A + X$	Operating lifetime of the durable product (A′)	[time]
T_B	Operating lifetime of product (B)	[time]
X	Extension of operating time of the product	[time]
β	Variation of the cost due to the purchasing of the product (B) substituting the product (A)	[%]
ρ	Variation of the costs due to the maintenance expenditure of the product (B) substituting the product (A)	[%]
σ	Variation of the costs due to the auxiliaries materials of the product (B) substituting the product (A)	[%]

components, the repair costs and the discount rate.

The value of some of these cost items can be expressed through the introduction of specific parameters. For instance, the purchase price (C_B) of the replacing product can be expressed as a function of the purchase price (C_A) of the product (A). A Similar approach is used for the costs for the maintenance and the auxiliary components of the product (B):

$$C_B = (1+\beta)\cdot C_A \tag{9}$$

$$M_B = \rho\cdot M_A \tag{10}$$

$$AU_B = \sigma\cdot AU_A \tag{11}$$

Due to the general difficulty to have robust values concerning the prices of a more durable product (A') compared to the base-case product (A), a simplifications is introduced by assuming that these two cost items are equal (i.e. $C_A = C_{A'}$). This assumption can be checked afterwards during a sensitivity analysis.

Moreover, the cost related to the energy consumption can be calculated by multiplying the energy consumption (e_n) by the specific cost per "kWh" (E_n). The energy efficiency of the substituting product (B) can be higher, lower or equal to that of the product (A). However, as discussed in Ardente and Mathieux (2014b), when the product (B) consumes the same or more energy compared to (A), the extension of the lifetime of product (A) is always beneficial. Therefore, the present analysis refers only to the case in which the energy consumption (e_B) of the product (B) is lower compared to that one of the base-case product (e_A). The costs for the energy consumption of (B) can be expressed as a percentage of the costs for the energy consumption of (A):

$$\frac{e_B}{e_A} = \delta; \quad E_{B_t} = e_B\cdot E_t = \delta\cdot e_A\cdot E_t, \quad \delta > 0 \tag{12}$$

The difference between the life cycle costs of the two scenarios is calculated as:

$$\Delta C_{TOT} = (\mathrm{PVF}_{t,i}C_A) + (\mathrm{PVF}_{t,i}C_B)\cdot\frac{X}{T_B} - (\mathrm{PVF}_{t,i}C_{A'}) + \sum_{t=1}^{X}\{\mathrm{PVF}_{t_B,i}[\times(\delta\cdot e_{A,t}\cdot E_t) + (\rho\cdot M_{A,t}) + (\sigma\cdot A_{A,t})]\} - \sum_{t_1=T_A+1}^{T_A+X}[\mathrm{PVF}_{t_A,i}(e_{A,t}\cdot E_t + M_{A,t} + A_{A,t})] - \mathrm{PVF}_{t,i}(R_{A'}) \tag{13}$$

Consistently with the environmental assessment, the economic durability index ($D_{economic}$) is defined as the ratio (in percentage) between the difference of the total costs of the two considered scenarios and the costs of the Base-case scenario, as following:

$$D_{economic} = \frac{\Delta C_{TOT}}{C_{TOT,base\ \ case}}\cdot 100 \tag{14}$$

5. Application of the Pro-EnDurAncE indexes to a case-study vacuum cleaner

Household appliances have been recognised by the European Climate Change Programme (ECCP) among those products "offering a high potential for cost-effective reduction of greenhouse gas emissions" (EU, 2009). In this context, "vacuum cleaners" (VCs) represent one of the product groups for which durability requirements have been introduced in the EU legislation (EU, 2013a). In particular, Ecodesign requirements for the durability of VC have been enforced for the hose ("the hose, if any, shall be durable so that it is still useable after 40,000 oscillations under strain") and the operational motor lifetime ("the operational motor lifetime shall be greater than or equal to 500 h") (EU, 2013a). The assessment of the compliance to these requirements is performed according to the existing standards (CENELEC, 2012; IEC, 2011). Moreover, starting from 01/09/2017, new maximum energy consumption thresholds will enter into force for the VCs (EC, 2014a; EU, 2013a). Therefore, it is expected that future generation of VCs entering the market will be more and more efficient. Based on these considerations, the VC product group was identified as relevant case-study to which apply the Pro-EnDurAncE indexes in order to assess the potential tradE–offs related to the extension of the lifetime.

The calculation of the indexes was preceded by a literature review on VCs to identify relevant aspects related to their life cycle and durability and collecting other relevant information for the analysis (e.g. available studies discussing the life cycle impacts and costs of VCs, repair options and consumer behaviour). This review on VC highlighted the lack of detailed LCA studies and, in general, the lack of quantitative environmental analyses about the durability of this product. Moreover, available information have been generally presented as aggregated and, therefore, it was difficult to extrapolate specific information about the composition of the VCs and details about its life cycle stages. For these reasons, the literature review on VCs was complemented by the analysis of studies focusing on the durability of other EEE.

From this investigation it is derived that VCs are "usE–phase" dominant products, although the impacts due to the manufacturing phase are always relevant, especially the impacts due to the production of the motor and printed circuit board (PCB).

The expected lifetime of VCs is ranging between 5 and 9 years (AEA, 2009; Brook Lyndhurst Ltd, 2014; CESA, 2011; Classic Cleaners, 2015; Johnston, 2013; Kobayashi et al., 2005; Maurer, 2010; White et al., 2013), even if some sources point out longer periods (AchooAllergy, 2015; Lee, 2015; Miele, 2013; Vacuumcleaner.org, 2015).

Maintenance and repair of the VCs were also recognised as essential aspects for the product lifetime, from both the environmental and economic points of view. Rose (2000) pointed out that the wear-out life of a VC is higher than its technological cycle, meaning that the replacement of a VC is not always associated to a failure. Replacement of a VC can be triggered by product innovation on the market, as for example illustrated by growing sales of bagless VCs in the European market in the last decades (Kemna et al., 2005). Simultaneously, new materials and also secondary raw materials are used for the production of VCs (AEA, 2009; Kobayashi et al., 2005). Concerning the repair operations, the most common failures of VCs are associated to the breakage of some components (as the hose, the belt, the agitator brush, the canister case or the cables), and the loss of performance for the suction. Motor failures (essentially due to the wearing of the carbon brushes) usually correspond with the disposal of the VC (AEA, 2009).

The literature review on the durability of VCs underlined also the relevance of the availability of the spare parts, and of the accessibility to some components for their repair/substitution. In some cases it was observed the availability for the consumers of very detailed information for the ordinary and extraordinary maintenance of some VC models, including information for the replacement of the motor (Dyson, 2015; IFIXIT, 2015).

Finally, some cost items were identified as key factors for the VC durability, especially the cost for the purchasing of a new product compared to the cost for repair (Barba-Gutiérrez et al., 2008; Hur et al., 2005; Kobayashi et al., 2005).

5.1. Detail of the case-study product and main assumptions for the analysis

Consistent with market sales in the last decades (AEA, 2009), the selected case-study product was a packaged bagged canister VC. The bill of materials (BoM) of the VC were obtained by dismantling a canister appliance and complementing this information with additional data from the literature (Table 4).

Consistently with this literature analysis, authors assumed that the case-study VC had 10 years of average operational life (corresponding to 500 h, assuming/estimating an average use of 50 h per year). It was observed that the majority of VCs currently put into the market belongs mainly to the European energy class 'A' and only a small amount to class 'B'. Moreover, it is expected that in the next future the large majority of VCs will belong to energy class 'A' or higher. Therefore, it was hypothesised that the case-study VC belongs to the energy label class 'A' (corresponding of 25 [kWh/year] (EU, 2013b)).

Finally, it was assumed/considered that the energy consumption of the replacing product (B) ranged from 70% to 100% of the consumption of (A). For example, a value of "δ" equals to 85% means that the product (B) consumes 15% less energy than (A).[2] Consistently with the literature review, the extension of the operating time (X) was assumed ranging from 0 to 300 h.[3]

All the main assumptions for the environmental and economic assessment of the durability of the case-study VC are summarized in Table 5.

5.2. Life cycle impacts of the case-study product

The environmental impacts of the base-case VC were calculated following a life cycle approach. The "GaBi software" and "Thinkstep" database (PE Europe GMBH, 2011) were used as data sources for the life cycle inventory data of materials, energy sources and process, and for the calculation of the life cycle impacts. In particular, impact categories recommended by the European Product Environmental Footprint were adopted (EC, 2013b).[4] The results of the impact assessment are reported in Table 6. These values represent the input data for the calculation of the durability index as illustrated in section 3.

5.3. Environmental assessment of durability

The environmental durability index "D_n" of the VC were calculated according to formula (5) for the impact categories considered in section 5.2. However, it was observed that the results for some impact categories had similar trends. In particular, the results of the index can be subdivided in three groups: 1) results for impact categories largely influenced by the impacts due to the energy consumption during the use phase (as the Global Warming Potential - GWP, acidification potential, ozone depletion potential, particulate matter/respiratory inorganics, photochemical ozone formation, primary energy from non-renewable resources, terrestrial eutrophication); 2) results for impact categories largely influenced by the impacts during the production phase (as the Abiotic Depletion Potential - ADP, and the ecotoxicity for aquatic fresh water); and finally 3) results for impact categories equally influenced by both the above mentioned phases (as the Human toxicity cancer effects - HTc, the freshwater eutrophication, the human toxicity non-cancer effects, the ionizing radiation, and the marine eutrophication). Therefore, for the analysis in the following section three exemplary impact categories were shortlisted as representative for each previous group (i.e. GWP for group 1, ADP for group 2 and HTc for group 3). This restricted sample of results allows to focus in a concise way on the

[2] According to the EU energy labelling scheme, a 15% more energy efficient product corresponds about to one energy efficiency class higher (EU, 2013b).

[3] There are examples of VCs in the market lasting up to 1000 h, especially those using motors without carbon brushes (AchooAllergy, 2015; Miele, 2013; WRAP, 2011).

[4] The land use and the water resource depletion impact categories were excluded (due to limited life cycle inventory data), while resource depletion impact was subdivided into the Abiotic Depletion Potential, mineral resources and Primary energy from non-renewable resources (net calorific value).

Table 4
Bill of materials of the case study vacuum cleaner.

Component	Material	Quantity [g]	Note
Motor	Al	7	Additional details on the composition of these components derive from:
	BMC-GF	133	- motor: (De Almeida et al., 2013, 2008; European Alliance, 2011;
	brass	99	Horie, 2004; Olivetti et al., 2012; Wong, 2009)
	copper	16	- bulk moulding compound – glass fibre (BMC-GF): MATBASE (2004),
	graphite	267	Prospector (2015)
	others	24	
	PE	158	
	PP	259	
	rubber	13	
	steel	885	
Hose	ABS	461	
	PE–HD	214	
	PP	18	
	rubber	3	
Canister case	ABS	2004	
	others	8	
	POM	42	
	rubber	2	
	steel	4	
Cable	brass	2	Details about the plastics composition of cord are derived from
	copper	7	Baitz et al. (2004)
	PE	15	
	PVC	137	
Cord reel assembly	ABS	2	
	brass	89	
	copper	142	
	PE	21	
	PVC	52	
	rubber	4	
	steel	194	
Dust bag	paper	40	Additional information, particularly about the amount of dust-bags used per year are derived from AEA (2009), Abele et al. (2005) and Kemna et al. (2005).
Filter	PE	17	Additional information, particularly about the amount of filters used per year are derived from Accumulair.com (2015), AchooAllergy.com (2015), AEA (2009), Dyson Company (2015a, 2015b) and Miele (2015)
Nozzle	ABS	47	
	PE	20	
	PP	224	
	steel	19	
PCB	PCB	12	Additional information, particularly about the amount of filters used per year
	steel	14	are derived from the PE database (PE Europe GMBH, 2011) and
	PP	209	Shenzhen Longood Electronics CO.L (2015)
	ABS	47	
Wheel	PE	20	
Packaging	Cardboard	1100	Packaging was modelled based on information derived from AEA (2009),
	LDPE	60	Philips (2016), Suzhou KVC Electric Co. Ltd (2016) and WRAP (2013)
	Paper (Manual)	100	
TOT		6981	

discussion of the methodological aspects of the durability index, without than extending the focus on several different impact categories. It is also highlighted that the selection of these exemplary impacts does not imply a judgment of their higher relevance (or weight) compared to other impacts. Decision makers applying the durability indexes should identify the impact categories more relevant for the objective of their study.

The potential impacts ($P_{B,n}$) due to the production of the replacing product (B) as well as the potential additional impacts ($P_{A',n}$) due to the manufacturing of the more durable product (A′) were estimated through the two parameters "γ" and "α". Similarly to the analysis of other household appliances (as washing machines discussed by Ardente and Mathieux, 2014a), it was assumed that newer product may have some different impacts related to changes in the product composition and manufacturing process. It was performed an analysis of the life cycle impacts of the case-study VC by assuming the use of a more complex PCB. The largest variation of the impacts was observed for the ADP (around 10%), whereas other impact categories remained almost unaltered. Therefore, "γ" was assumed 110% for the ADP and 105% for all the other impact categories. On the other hand, the additional impacts necessary to make the product (A′) more durable (represented by the parameter "α") can be related, for example, to additional materials (e.g. plastics or metals) employed for the manufacturing of the VC's components. Coherently with observations by AEA (2009), it was considered that, compared to the Base-case scenario, product (A′) would require additional 20% of plastic for the hose, nozzle, casing and wheels, and additional 5% of the mass of each material in the motor and cables. It resulted that these assumptions slightly affected the HTc and the ADP impact, while they were almost negligible for the GWP. Therefore, the following values of "α" were assumed: 1% for GWP; 4% for ADP; and 7% for HTc. A sensitivity analysis of parameters "α" and "γ" is illustrated at the end of the present section.

Consistently with Ardente and Mathieux (2014b), it was

Table 5
Summary of the assumptions for the calculation of the durability index.

Parameter	Value	Note
Average operating time (T_A)	10 [years] 500 [hours]	
Yearly energy consumption until 500 h	25 [kWh/y]	
Extension of the lifetime (X)	0 → 300 [hours]	
Variation of the manufacturing impact of product (B) compared to (A) (γ)	$\gamma = 105\%$ ($\gamma = 110\%$ for ADP)	For the sensitivity analysis γ is assumed to vary in the range $103\% \le \gamma \le 107\%$ ($90\% \le \gamma \le 130\%$ for ADP)
Variation of the energy consumption impact of product (B) compared to (A) (δ)	$70\% < \delta < 100\%$	
Variation of the additional impacts of durable product (α)	$\alpha = 1\%$ for GWP $\alpha = 4\%$ for ADP $\alpha = 7\%$ for HTc	For the sensitivity analysis α is assumed to vary in the range: $0\% \le \alpha \le 2\%$ for GWP; $3\% \le \alpha \le 5\%$ for ADP; $6\% \le \alpha \le 8\%$ for HTc,
Price of product (A) (C_A)	150 [€]	Information about purchasing price of VCs were collected by the following sources: (AEA, 2009; Wollerton, 2013). For the sensitivity analysis C_A is assumed to vary in the range $100€ \le C_A \le 200€$
Price of product (B) (C_B)	$(1+\beta) \cdot C_A$ $\beta = 20\%$	For the sensitivity analysis β is assumed to vary in the range $-15\% \le \beta \le 25\%$
Price of more durable product (A′) ($C_{A'}$)	170 [€]	For the sensitivity analysis C_A is assumed to vary in the range $150€ \le C_A \le 200€$
Price of electricity (El_{t_1})	0.205 [€/kWh]	Information about purchasing price of VCs were collected by the following sources: (EUROSTAT, 2015)
Growth rate of electricity price	4%	Information about purchasing price of VCs were collected by the following sources: (EC, 2014b) For the sensitivity analysis the growth rate of electricity price is assumed to vary in the range 1% ÷ 7%
Discount rate (i)	3%	Information about purchasing price of VCs were collected by the following sources: (Iraldo and Facheris, 2015). For the sensitivity analysis “i” is assumed to vary in the range $1\% \le i \le 5\%$
Repair costs (R)	$20\% \cdot C_A$	The repair expenditures will occur after 11 years lifetime of product A. For the sensitivity analysis R is assumed to vary in the range $0\% \cdot C_A \le R \le 40\% \cdot C_A$
Auxiliaries costs (AU)	1.75 [€/dustbag]	For the sensitivity analysis A is assumed to vary in the range $1.5€ \le AU \le 2€$
Maintenance costs (M)	2 [€/set of filters]	For the sensitivity analysis A is assumed to vary in the range $2€ \le M \le 14€$

Table 6
Life cycle Impact Assessment of the case-study vacuum cleaner.

Impact category	Unit of measure	TOT	Manufacturing	Use phase			EoL
				Auxiliaries components	Ordinary maintenance and dust-bags	Energy consumption	
Abiotic Depletion Potential, mineral resources (ADP-res)	kg Sb_{eq}	1,27E−03	1,21E−03	9,76E−07	1,80E−07	6,09E−05	9.16E−07
Acidification Potential (AP)	Mole of H^+_{eq}	8,04E−01	1,20E−01	4,06E−03	1,60E−03	6,70E−01	8.64E−03
Ecotoxicity for aquatic fresh water (FET)	CTUe	7,78E+01	7,39E+01	2,21E−01	5,09E−02	3,52E+00	1.22E−01
Freshwater eutrophication (EPf)	kg P_{eq}	3,79E−04	1,61E−04	6,50E−05	5,42E−07	1,48E−04	4.17E−06
Human toxicity cancer effect (HTc)	CTUh	3,37E−07	2,11E−07	1,48E−08	3,92E−09	1,02E−07	4.99E−09
Human toxicity non-cancer effect (HTnc)	CTUh	9,18E−06	6,22E−06	2,70E−08	1,79E−08	2,86E−06	4.92E−08
Ionizing Radiation (IR)	kg $U235_{eq}$	5,59E+01	2,77E+01	−1,27E−02	3,83E−02	2,44E+01	3.68E+00
Global Warming Potential (GWP)	kg $CO_{2\,eq}$	1,49E+02	2,72E+01	1,80E+00	4,24E−01	1,18E+02	1.59E+00
Marine eutrophication (Epm)	kg N_{eq}	1,06E−02	4,29E−03	8,04E−04	1,69E−05	5,19E−03	2.53E−04
Ozone Depletion Potential (ODP)	kg $CFC\text{-}11_{eq}$	1,11E−07	2,11E−08	−5,35E−11	1,39E−10	8,78E−08	1.82E−09
Particulate matter/Respiratory inorganics (PMF)	kg $PM2,5_{eq}$	4,94E−02	8,17E−03	1,26E−04	8,75E−05	4,04E−02	5.71E−04
Photochemical Ozone Formation (POCP)	kg NMVOC	3,18E−01	6,39E−02	4,56E−03	1,03E−03	2,46E−01	3.10E−03
Primary Energy Demand (PED)	MJ	2,76E+03	5,84E+02	2,27E+01	1,46E+01	2,11E+03	3.01E+01
Terrestrial eutrophication (EPt)	Mole of N_{eq}	1,13E+00	2,37E−01	1,88E−02	2,74E−03	8,62E−01	1.25E−02
Total freshwater consumption (FC)	UBP	1,60E+02	2,57E+01	8,94E+00	3,10E−01	1,24E+02	1.66E+00

assumed that the two products (A) and (B) had the same average lifetime and the same environmental impacts due to the end-of-life. Moreover it was assumed/considered that the two products used the same amount of auxiliary materials (dust-bags) during the operation (i.e. $AU_{A,n} = AU_{B,n}$).

The environmental impacts related to repair operations were estimated with the same approach illustrated by Ardente and Mathieux (2014b). In particular, the “low-repair scenario” (LRS) took into account minor repair operations (causing negligible additional impacts), while the “high-repair scenario” (HRS) assumed the substitution of some broken parts of the VC.[5] The impact for repair (R_A) in the HRS scenario were assumed to range between 1% and 3% of the life cycle GWP impact, and between 5% and 10% for the life cycle ADP and HTc impacts. A summary of the

[5] Parts more often substituted are the PCB, the hose and the nozzle plate (AEA, 2009; EC, 2013c). The performed LCA analysis demonstrated that the substitution of the PCB mainly affects the ADP (increase of 9.74% of the life cycle ADP) while the substitution of the hose and the nozzle is relevant for the HTc (increase of respectively 5.32% and 2.07% of the life cycle HTc).

Table 7
Summary of the impacts data used for the calculation of the environmental durability index.

	Global warming potential (GWP)	Human toxicity cancer (HTc)	Abiotic depletion potential (ADP)
$P_{A,n}$	2.72E+01 [kg $CO_{2\text{-}eq}$]	2.11E−07 [CTUh]	1.21E−03 [$kg_{Sb\text{-}eq}$]
E_n	1.59E+00 [kg $CO_{2\text{-}eq}$]	4.99E−09 [CTUh]	9.16E−07 [$kg_{Sb\text{-}eq}$]
$U_{A,n}$	2.37E−01 [kg $CO_{2\text{-}eq}$/hour]	20.3E−10 [CTUh/hour]	1.22E−07 [$kg_{Sb\text{-}eq}$/hour]
$R_{A,n}$	LRS 0.0E+00	LRS 0.0E+00	LRS 0.00E+00
	HRS 8.17E−01	HRS 1.06E−08	HRS 6.06E−05

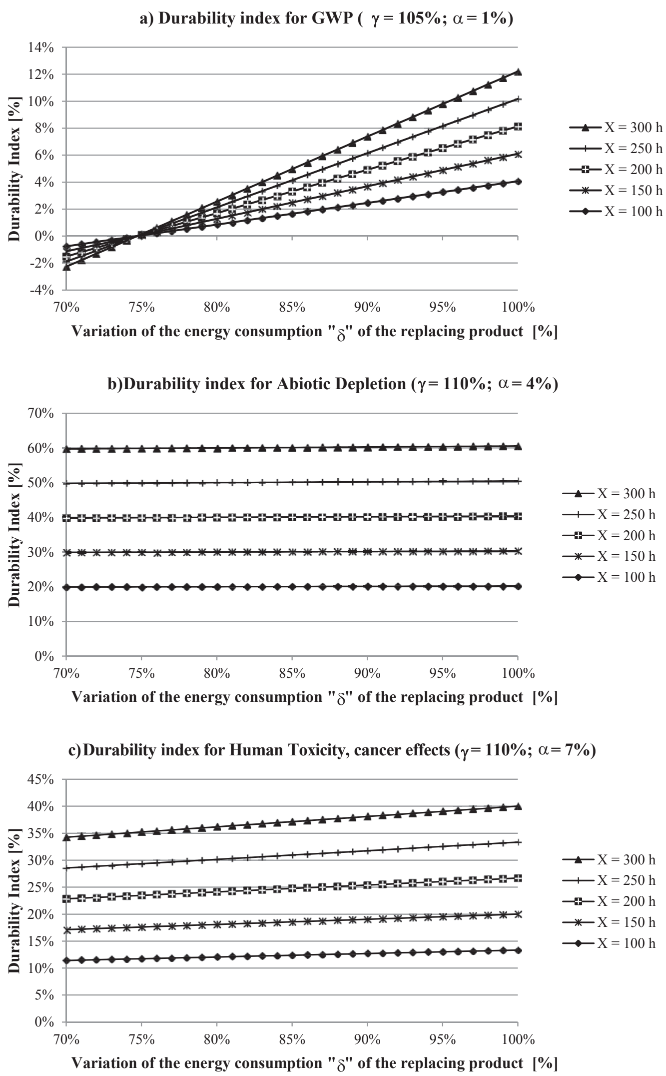

Fig. 3. Durability index for the canister vacuum cleaner for the Low Repair Scenario "LRS" for three representative impact categories: Global Warming Potential (a), Abiotic Depletion (b) and Human toxicity cancer effects (c).

input data for the calculation of the durability index for the VC is illustrated in Table 7.

Fig. 3 and Fig. 4 illustrate the durability index "D_n" for the LRS and HRS respectively. It resulted that:

- the extension of the lifetime of the VC can produce some environmental benefits, from a life cycle perspective, even when this implies a delay in the substitution with a more energy efficient VC. For example, in the LRS scenario, the extension of the lifetime of the VC by 100 h (i.e. 2 years) saves around 1.7% of GWP compared to the replacement of the VC with a 15% more efficient one (Fig. 3a). The replacement becomes convenient, for the GWP impact, when the base-case product is substituted by a VC 25% or more energy efficient, i.e. for values of: $\delta < 75\%$ (Fig. 3a).
- the higher is the environmental lifetime extension, the higher can be the environmental benefits, and this particularly emerges for the impact category dominated by energy consumption (i.e. GWP) (Fig. 3a). Compared to the replacement of the base-case VC with a new one 15% more efficient, a lifetime extension of 250 h reduces the GWP by 4.2% (Fig. 3a);
- the environmental benefits are more relevant for the impact categories dominated by the production phase (e.g. HTc and ADP) (Fig. 3 b and Fig. 3c). For example, in the LRS scenario, the extension of the lifetime of the VC by 100 h (i.e. 2 years) saves around 20% of the ADP compared to the replacement of the VC with a 15% more efficient one (Fig. 3b).;

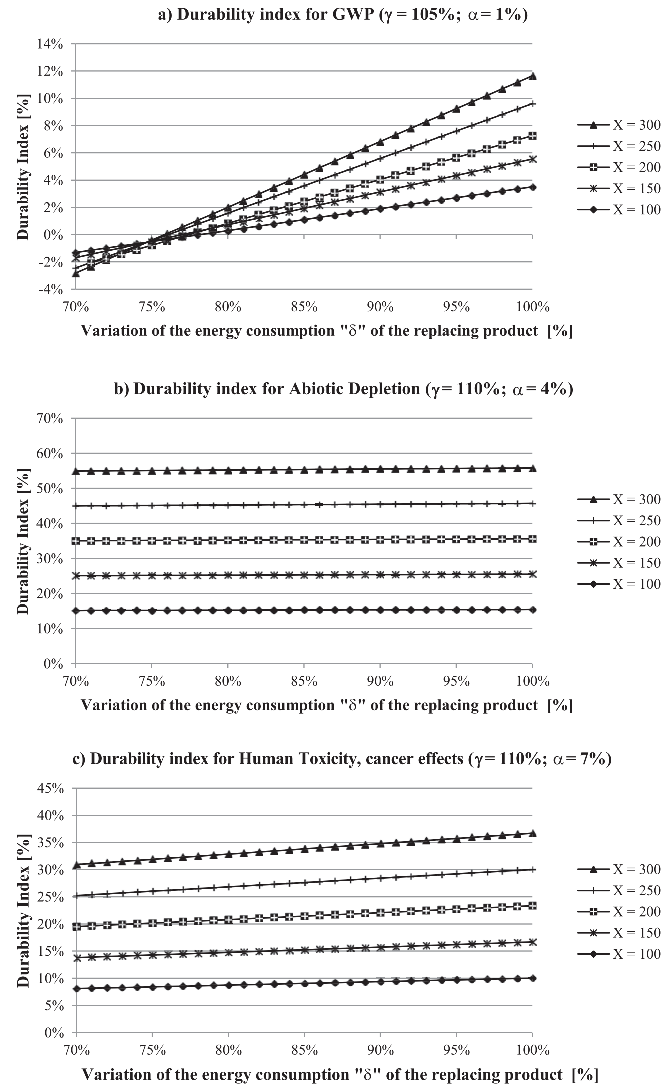

Fig. 4. Durability index for the canister vacuum cleaner for the High Repair Scenario "HRS" for three representative impact categories: Global Warming Potential (a), Abiotic Depletion (b) and Human toxicity cancer effects (c).

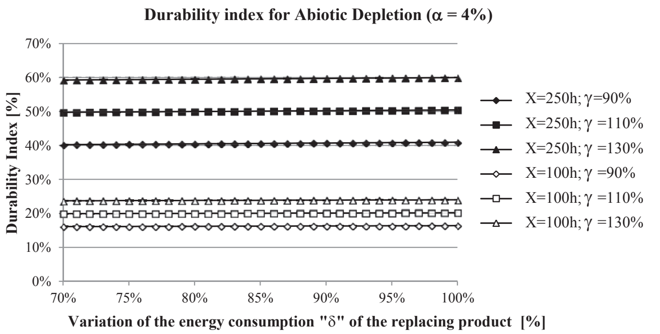

Fig. 5. Durability index for the canister vacuum cleaner for two different lifetime extensions (X = 100 h and X = 250 h) on varying γ-parameter.

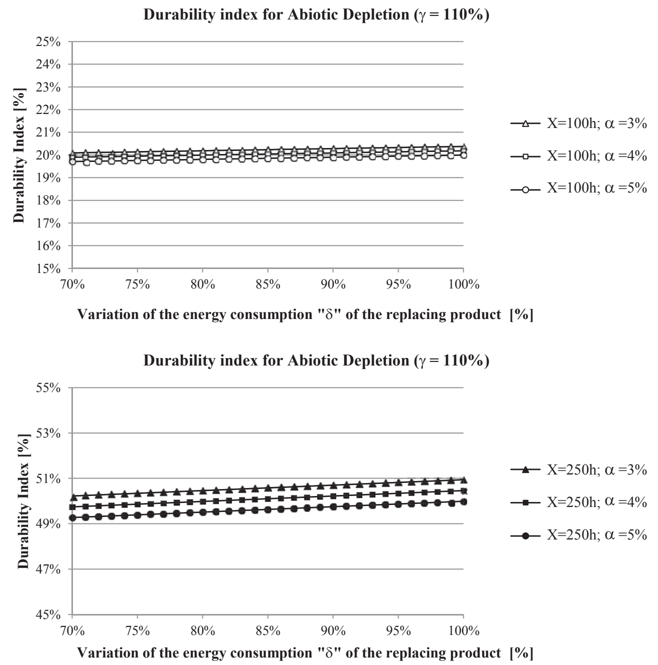

Fig. 6. Durability index for the canister vacuum cleaner for two different lifetime extensions (X = 100 h and X = 250 h) on varying α-parameter.

- the HRS discloses lower environmental benefits compared to the LRS (Fig. 4). This difference is more relevant for the impact categories dominated by the production phase (Fig. 4 a, Fig. 4 b and Fig. 4c). For example, in the HRS scenario, the extension of the lifetime of the VC by 100 h (i.e. 2 years) saves around 15% of the ADP compared to the replacement of the VC with a 15% more efficient one (Fig. 4b).

Finally, in order to handle the uncertainties due to previous assumptions, a sensitivity analysis was performed for the parameters "γ"[6] and "α", as detailed in Table 5. Higher variation ranges of the parameters were assumed for the ADP, since this is the impact category more affected by changes of the product composition of the manufacturing processes. The results pointed out that these variations of the parameters "γ"and "α" do not largely affect the "D_n" index for the GWP impact, whereas some variations are observed for the ADP and HTc impacts (Figs. 5 and 6). For instance, considering a lifetime extension of 250 h, the GWP varies less than 0,5% when varying "γ" by ±2%. The ADP varies up to 10% when "γ" varied by ±20%. Considering the ADP impact category (Fig. 5), the results highlighted that the higher is manufacturing impact of the replacing product (i.e. higher values of "γ"), the higher are the environmental benefits of the Durability scenario. Moreover, the variation of "D_n" is higher for higher extension of the lifetime (X) (Fig. 5). Finally, the additional impacts due to the production of more durable products ("α") is more relevant for high value of lifetime extension. However, the variation of "α" does not largely affect the "D_n" when referring to the ADP impact category (Fig. 6).

5.4. Economic assessment of durability

The index for the economic assessment of durability were applied to the same case-study VC described in the previous section. Repair costs until 500 h were assumed to be null[7] and the purchasing price of the more durable product (A') was considered equal to the purchasing price of the product (A). According to European statistics (EC, 2014b), the increase of the annual price of the electricity was estimated assuming a 4% growth rate of the price of the electricity for household. Similarly, the discount rate (i) was assumed as 3%. Input data for the economic analysis are summarized in Table 5, while the Life Cycle Costs (LCC) of the Base-case and the Durability scenarios and the results of the economic

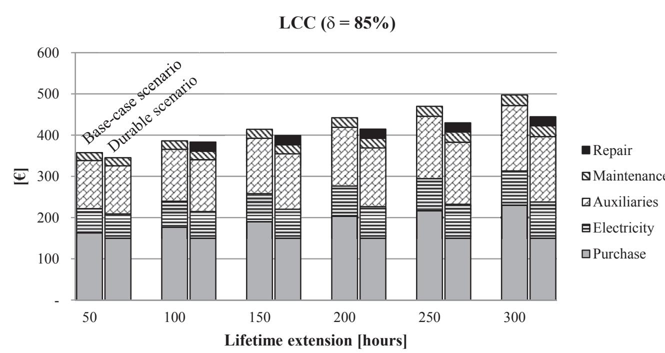

Fig. 7. Life cycle costs of the Base-case (first column) and the Durable scenario (second column).

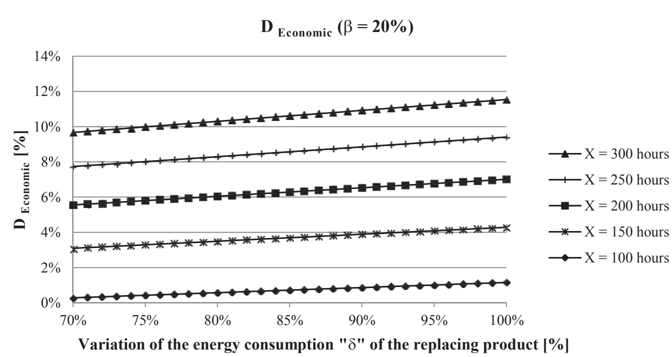

Fig. 8. Economic durability index for the canister vacuum cleaner. β is the parameter linking the purchase price of the old and the new VC ($C_B = \beta \cdot C_A$).

[6] Concerning the parameter "γ", values lower than 100% have been also assumed, in order to take into account that new manufacturing processes might have a lower impact in comparison to current processes due, for example, to the progress of manufacturing technologies.

[7] The European legislation on the Ecodesign of products fixed some durability requirements for the VC, as by the minimum lifetime of the motor (lasting more than 500 h) and of the hose (to be usable after 40,000 oscillations) (EU, 2013a). It is then plausible to assume that the VC will not suffer failures for these components before 500 h. Similarly, failures of other components are also excluded for the same time frame.

durability index ($D_{economic}$) are illustrated in Fig. 7 and Fig. 8 respectively.

The analysis of the LCC of the VC revealed the relevance of the purchase price and of the cost of auxiliary materials (C_A, C_B and AU). Their contribution is always higher than 30% of the LCC for both scenarios and for all the considered lifetime extensions. On the other hand, the costs due to energy do not strongly affect the difference between the LCC of the two scenarios: their contribution ranges between 16% and 20% of the case-study LCC (Fig. 7).

The durability index ($D_{economic}$) proved that the lifetime extension of VCs generally involves some economic benefits. For example, compared to the replacement of the base-case VC with a new one 15% more efficient, the extension of the lifetime by 250 h reduces the LCC by 8.6% (i.e. 40€) (Fig. 8). Moreover, the higher is the lifetime extension, the higher are the economic advantages. Differently from the environmental assessment of durability (e.g. for the GWP impact), the variation ("δ") of the energy consumption of the new product does not largely affect the durability index ($D_{economic}$) (the variation of "δ" implies, at the maximum, the 1.7% change of $D_{economic}$) (Fig. 8).

In order to check the relevance of each cost item, authors performed a sensitivity analysis of all the parameters illustrated in section 4. In particular, the following variation range was assumed: the purchasing price of product (A) between 100€ and 200€, based on data available on companies website; the parameter "β" related to the purchasing price of product (B) between 5% and 25%, to encompass the potential increase or decrease of the price of the replacing product; the purchasing price of product (A') between 150€ and 200€, based on data available on companies websites; the growth rate of electricity between 1% and 7%, based on the trends of households electricity price in the last years (EC, 2014b); the discount rate between 1% and 5%, consistently with observation in the literature (EC, 2013a; Davis, 2008; AEA, 2009); the cost of the auxiliary and the maintenance materials between 1.5€ and 2€ for dustbags and between 2€ and 14€ for filters, based on data available on companies websites.

Concerning repair costs, values of "R" were assumed to range between 0% and 40% of the purchase price of product (A). This wide range, higher compared to the range used for the environmental analysis, reflects that the repair operations can be more relevant in terms of costs than in terms of environmental impacts.

Results proved that the variation of the discount rate, the growth rate of electricity and the auxiliary materials do not significantly affect the final results. On the other hand, the variation of the repair costs, the maintenance costs and of the assumptions about the purchase prices of the products (base-case "A", durable product "A" and the replacing product "B") are more relevant. The repair costs can make the Durable scenario not convenient from the economic point of view (Fig. 9). For example, assuming the replacing product (B) 15% more efficient than the product (A), and assuming the repair costs (R) equal to 30% of the purchasing price of the product (A), the Durability scenario is convenient from an economical perspective only if the extension of the lifetime is higher than 130 h (i.e. 2.6 years).

6. Discussion and conclusions

The "Pro-EnDurAncE" indexes presented in this article proved to be a valuable tool to assess the benefits/impacts of extending the lifetime of EuPs from the environmental and the economic perspective.

In particular, the environmental durability index (D_n) allows to identify if and to what extent it is convenient to have a durable product, taking into account several important factors such as: impacts of repair/replacement of components; differences in the energy performances of different products; impacts due to the use of auxiliary materials and maintenance; and impact due the manufacture of more durable products. Similarly, the economic durability index allows to model some of the key factors that affect the economic viability of a durable product, for example the purchase price of VCs, the costs due to repair and auxiliary materials.

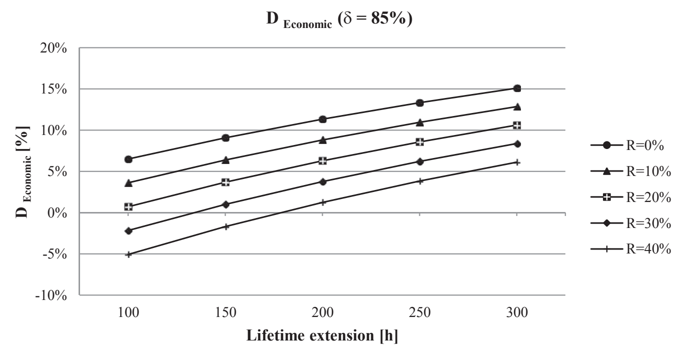

Fig. 9. Difference between the LC costs of the two canister vacuum cleaners (on varying R-values). The non-linear trend depends on the difference between the cost items related to the discount rate.

The durability indexes are sufficiently general to be applicable to different EuPs. Thanks to the introduction of a set of different parameters, the proposed durability indexes allow to model several aspects of the product that are generally uncertain or not know in some cases. The uncertainty of these parameters can be accounted through a sensitivity analysis by introducing sufficiently wide variation ranges. Thus, the indexes can be used both for assessing existing products, as well product under design (e.g. to assess the convenience of adopting some ecodesign strategies to make a product more durable). The indexes can be also useful to assess and support dedicated policies for the durability of products, as for example through the enforcement of durability requirements on minimum lifetime in the context of the European Ecodesign Directive.

The environmental durability index can be referred to different type of environmental impact categories. In principle, it could be possible to introduce an aggregated index obtained by the weighting of different results for different impact categories. Due to the large uncertainty of the weighting process, this was excluded by this analysis. However, this aspect could be part of future revisions and developments of the indexes.

Outcomes of the proposed assessment could be also used to inform the users about the durability products and to push the consumers for more conscious decisions. For example, users could be informed about the potential tradE−off between having a more durable product versus the purchasing of a more efficient one, or about the convenience of repairing a product instead than discarding it.

It is also recognised that the durability of products is a wide and complex issue involving many aspects. For instance, the consumer behaviour is fundamental in terms of appropriate use, maintain and disposal of the appliances (e.g. to grant the energy efficiency of the product throughout the lifetime). Moreover, the consumer choices are influenced by psychological aspects not directly related to economic costs or environmental aspects, as for example: fashion issues, product's characteristics and functions, changes of user's needs, product's obsolescence and technological changes of products in the market. Although very difficult to be modelled by quantitative parameters, these aspects could be part of future developments of the method.

The application of the indexes to the VC case-study produced some relevant conclusions. The results showed that the extension of the lifetime of a VC generally implied some benefits, both environmental and economic, in the large majority of considered scenarios. In general, these benefits already occur for small extension of the lifetime and they become more relevant when the lifetime of the product is extended further. In particular, the environmental benefits are variable depending on the considered impact category. Higher benefits are associated to impact categories dominated by the manufacturing, but some benefits were also measured for impact categories dominated by the consumption of energy during the operation (e.g. GWP). Results also highlighted the relevance of the reparability of the product for both the environmental and economic assessments. Even though the impacts and costs of repairing obviously imply a decrease of the benefits, repairing the VC is generally environmentally and economically convenient. Moreover, the cost analysis proved the importance of some cost items, such as purchase price of the products, of the maintenance and of the auxiliary materials. Interestingly the use of auxiliary and the maintenance materials were instead not so relevant for the environmental assessment. This consideration proved the relevance of having a multi-criteria approach for the assessment of durability.

All these results could be used to promote the design of more durable VC, for example through the enforcement of more ambitious policy measures. For example, ecodesign requirements on the minimum lifetime of the motor and hose of the VC, as introduced by the European Commission, could become even more stringent in the next future. It is also recommended the application of the indexes to additional case-studies in order identify products that are beneficial when durable and to contribute in this way to the application of the EU principles for a circular economy.

Disclaimer

The views expressed by the authors in the article are personal and do not necessarily reflect the official position of the European Commission.

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